# Axions in neutron star mergers

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Harris, Fortin, Sinha, Alford, arXiv:2003.09768

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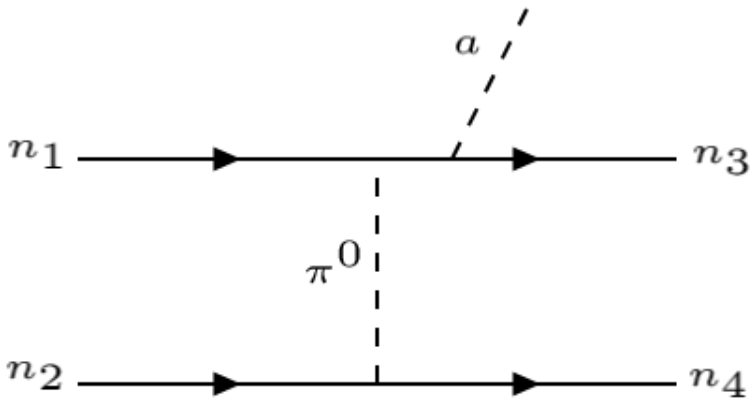
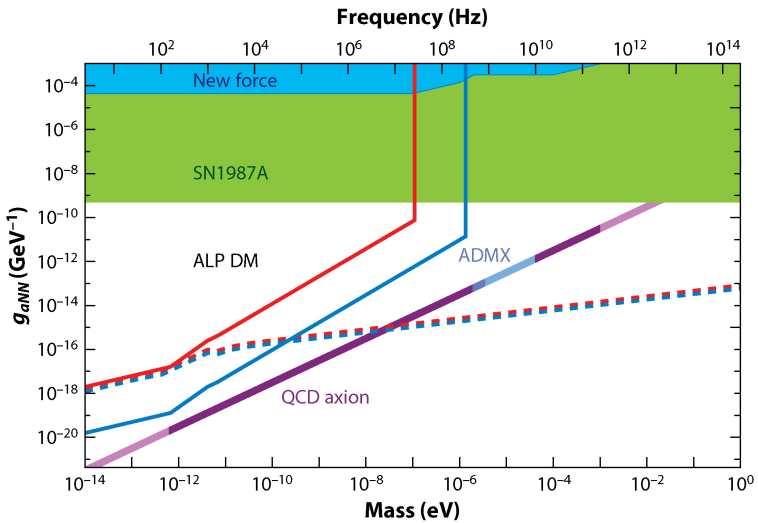
# Axions and their interactions

- Axions are very light ($m_a \ll 1$ eV) bosons.
  - Axions are ultrarelativistic ($E_a \approx |\mathbf{p}_a|$) in dense matter.
- Produced by neutron bremsstrahlung $n + n \to n + n + a$
  - $\mathcal{L} = G_{an}(\partial_\mu a)\bar{n}\gamma^\mu\gamma_5 n$




Graham PW, et al. 2015.
Annu. Rev. Nucl. Part. Sci. 65:485–514

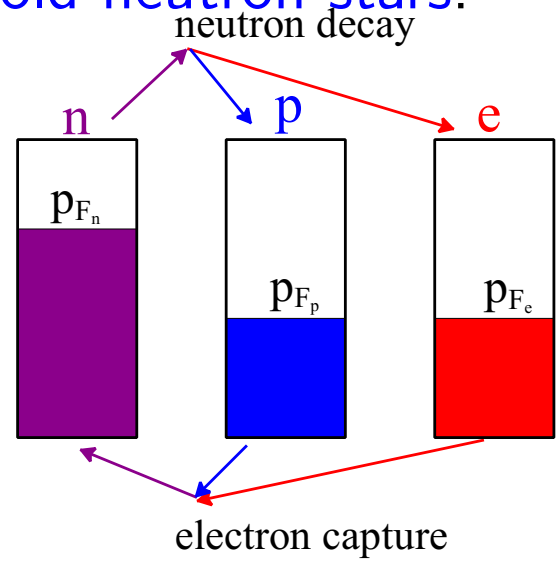
## Axion-neutron coupling

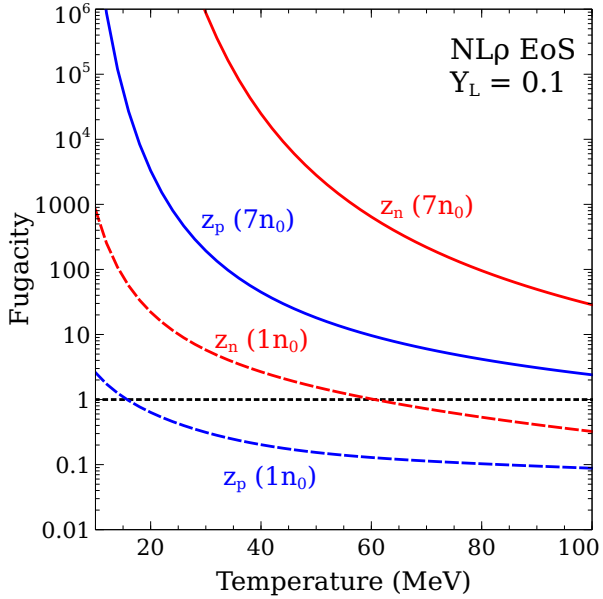
- $G_{an}$ and $m_a$ are proportional for the QCD axion.
- SN1987A constrains coupling $G_{an}$ to small values.

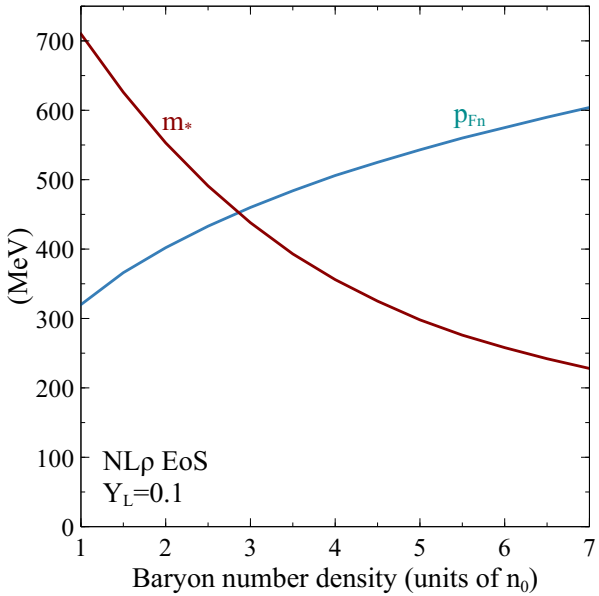
Axions are produced in neutron-rich environments. What role do they play in neutron star mergers?

# Nuclear matter in neutron star mergers

Cold neutron stars:




Neutron star mergers:

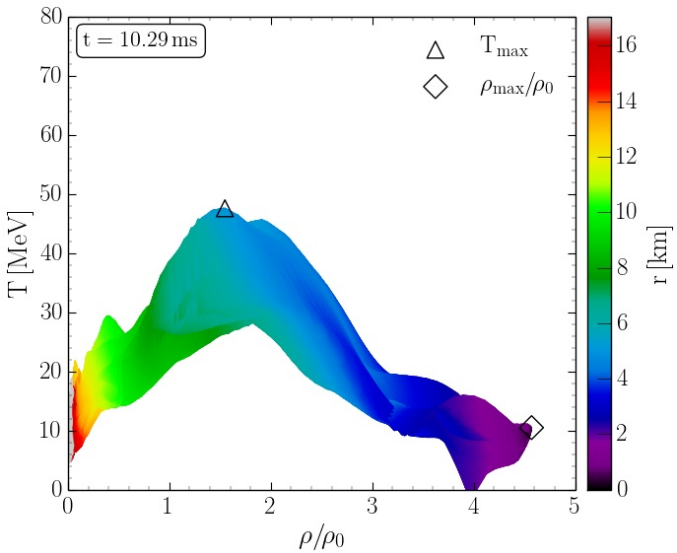


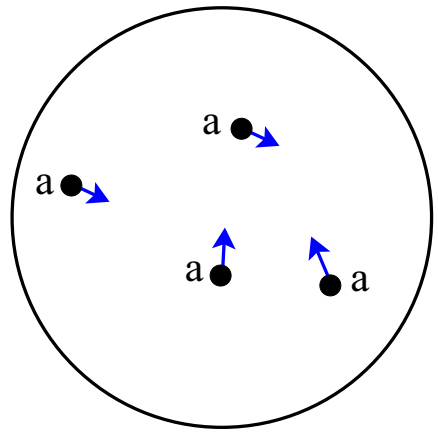

Figure courtesy of M. Hanauske.

Our calculations ($\lambda_a$ and $Q_a$) must consider:

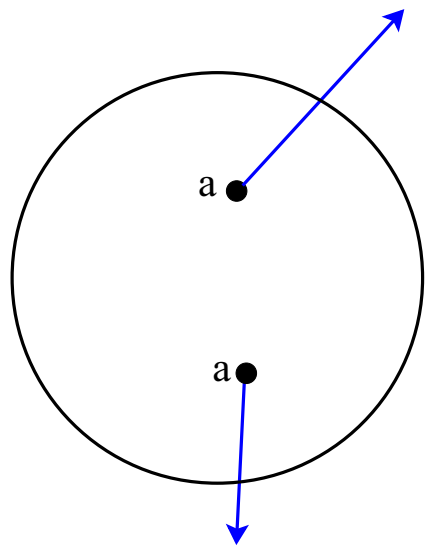
- Neutrons can be degenerate ($z_n \gg 1$) or non-degenerate ($z_n \ll 1$)
- Neutrons can be non-relativistic (at low $n_B$) or highly-relativistic (at high $n_B$)

# What can axions do in mergers?

- $\lambda_a < R$: If axions are trapped (like $n, p, e^-$) then they could thermally equilibrate matter in the merger




- $\lambda_a > R$: If axions escape from the merger, they cool it down.

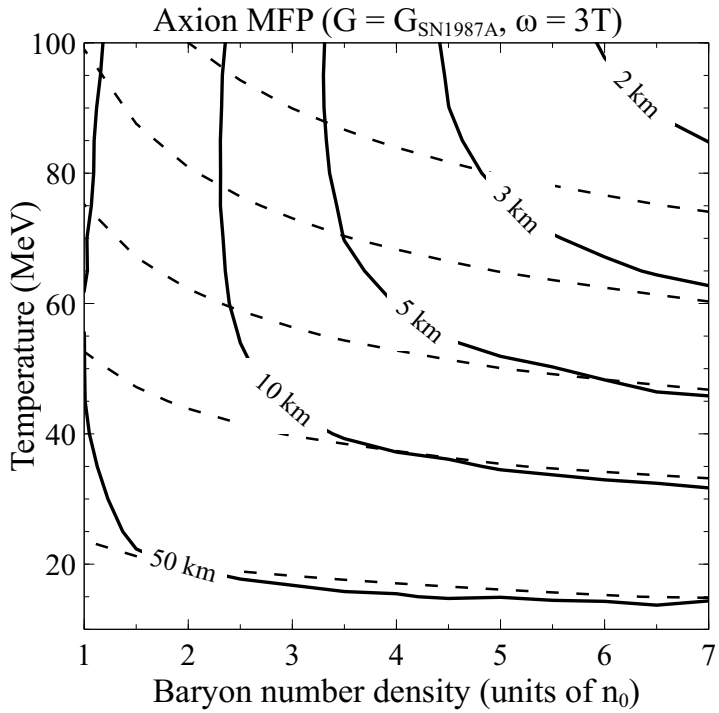


# Axion mean free path

Are axions trapped in neutron star mergers?

- Only if their mean free path (due to $n + n + a \rightarrow n + n$) is much less than 1 km ($R_{\text{merger}} \sim 20 - 30$ km.)

$$\lambda_a^{-1} = \int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\frac{d^3p_4}{(2\pi)^3}\frac{S\sum|\mathcal{M}|^2}{2^5E_1^*E_2^*E_3^*E_4^*\omega}(2\pi)^4\,\delta^4(p_1+p_2-p_3-p_4+\omega)f_1f_2(1-f_3)(1-f_4) \sim G_{an}^2$$




All other allowed values of $G_{an}$ yield longer axion mean free paths.

Axions free-stream through neutron star mergers.

# Axion cooling

Axions escape the merger, cooling it.

$$\frac{dT}{dt} = \frac{d\varepsilon\,/\,dt}{d\varepsilon\,/\,dT} = -\frac{Q_a}{c_V}.$$

## Specific Heat

- Dominated by the particle with the most low-energy excitations - in mergers, this is the neutron
- $c_V \sim p_{Fn}^2 \delta p = p_{Fn}^2 \underbrace{\left(\frac{m_{\rm eff}}{p_{Fn}} T\right)}_{T/v_{Fn}} = m_{\rm eff} p_{Fn} T.$

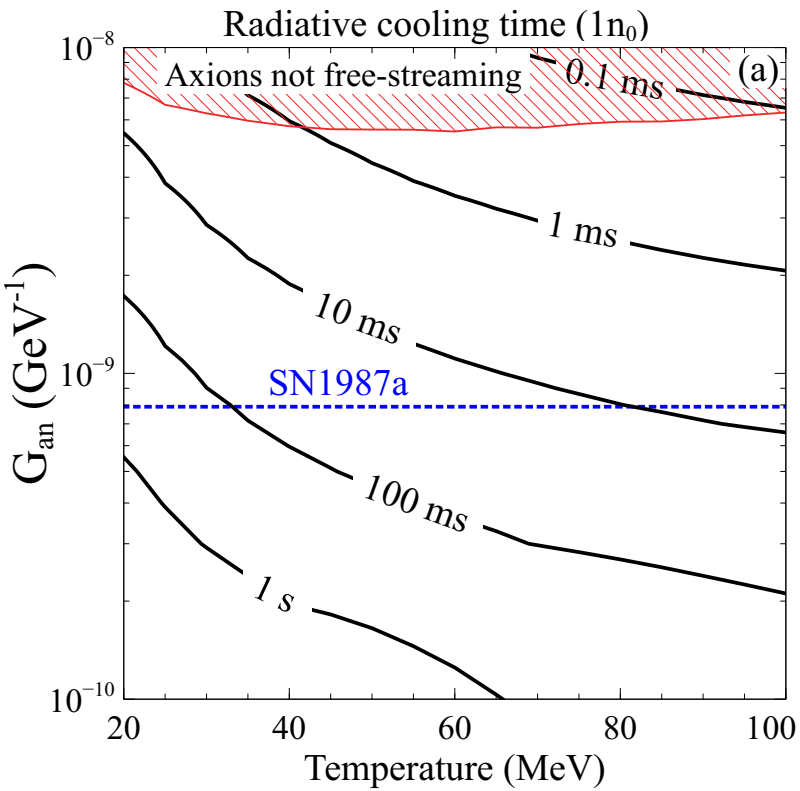
## Axion emissivity

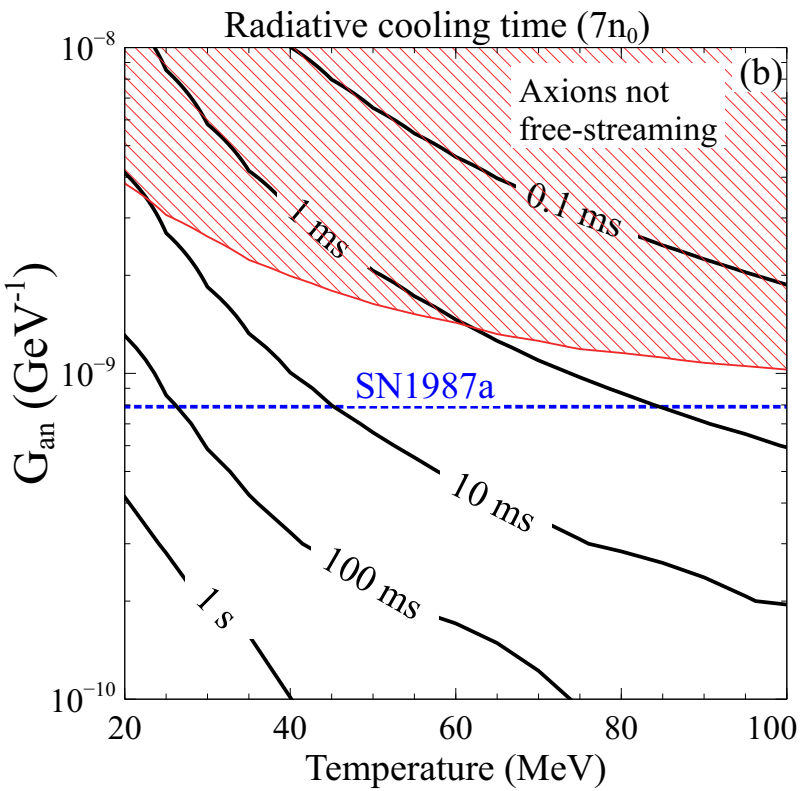
Amount of energy emitted in axions (per volume per time) due to $n + n \to n + n + a$.

$$Q = \int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\frac{d^3p_4}{(2\pi)^3}\frac{d^3\omega}{(2\pi)^3}\frac{S\sum|\mathcal{M}|^2}{2^5 E_1^* E_2^* E_3^* E_4^* \omega}\omega$$
$$\times (2\pi)^4\,\delta^4(p_1 + p_2 - p_3 - p_4 - \omega) f_1 f_2 (1 - f_3)(1 - f_4)\,.$$

# Axion cooling timescale

Merger remnants survive for tens of milliseconds.
Can axion cooling take place on this timescale, making it relevant for mergers?



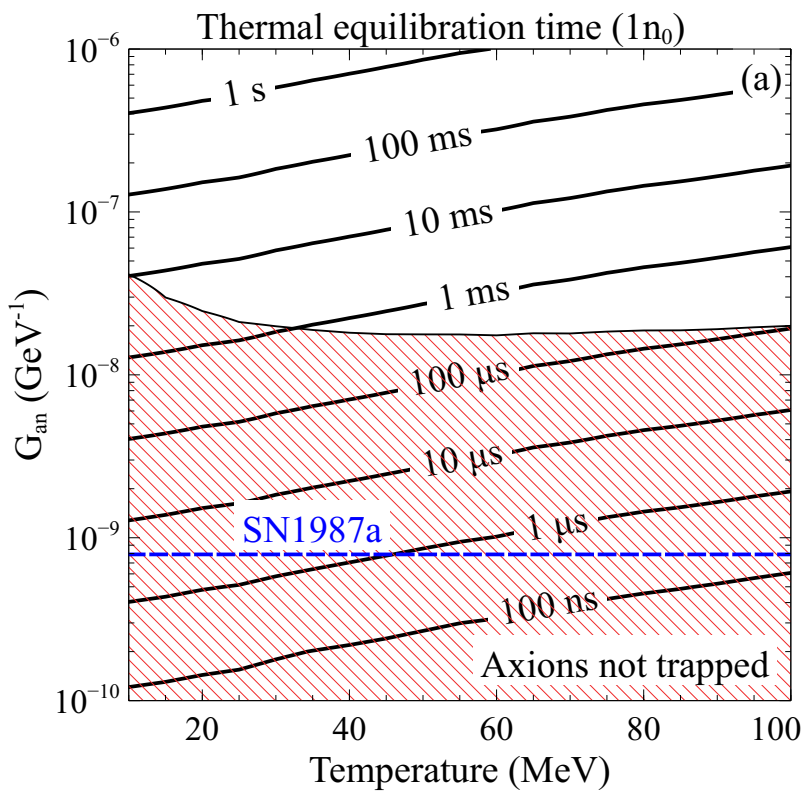




Significant cooling can occur in a few milliseconds!

# Thermal equilibration

If axions were trapped, they would help thermally equilibrate matter in a merger.

- Hot fluid element of size $z$ has excess thermal energy $E = c_V TV$
- Rate of energy transfer $W = \kappa(dT/dz)A$
- Timescale for thermal equilibration:
  - Specific heat $c_V$ is from neutrons
  - Thermal conductivity $\kappa$ is from axions
  - $\tau_\kappa \sim \frac{m_L p_{Fn} z^2}{T^2 \lambda_a}$



# Conclusions

- Axions have a long mean free path in merger conditions. When produced by $n + n \to n + n + a$, the axion escapes the merger, cooling it.
- Axion cooling could take place on merger timescales ($\sim 10$ ms) if the coupling is not too much lower than the SN1987A bound.
  - Very hot fluid elements could cool quickly via axion emission, even though they trap neutrinos.
- If axions or ALPs could be trapped, they would contribute to thermal equilibration in the merger.
  - QCD axions unlikely to be trapped, but other BSM particles could be...